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by

A.S. SELIVANOV, V.N. GOVOROV, A.S. TITOV, AND V.P. CHEMODANOV

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On 3 February 1966 the Soviet automatic station *Luna-9* was the first to achieve a soft landing on the surface of our satellite. One of the important tasks of this space experiment was the television investigation of the microstructure of the lunar surface that is fundamentally not discernible with terrestrial means of observation. The image of the lunar landscape was transmitted by means of a panoramic [wide-angle] TV camera *1* installed in the center of the upper portion of the automatic lunar station (fig. 1) which is a spherical container *2* having a low center of gravity. The station is oriented on the surface by means of four opening petals—antenna *3*. The field of view of the panoramic camera includes rod antennas *4* and narrow dihedral [two-faceted] mirrors *5* designed to obtain stereoscopic images in a restricted angle of view.

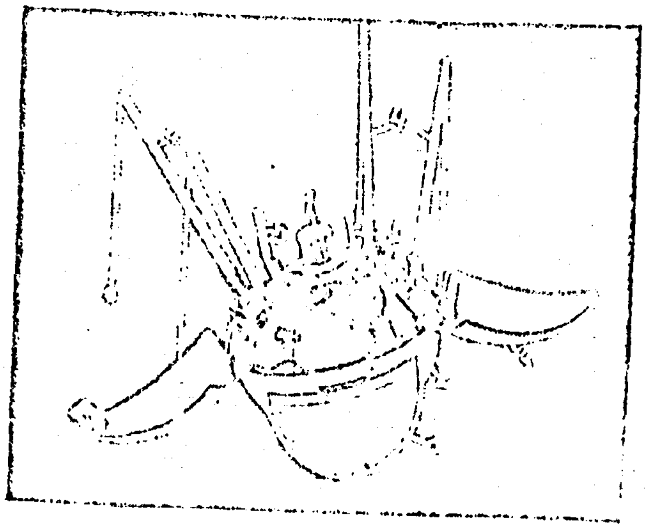

Figure 1

The station had no solar batteries, its operational resource was completely determined by the energy storage of the chemical power supplies installed aboard. In connection with this, naturally, quite rigid [strict] requirements in the economy of power were imposed on the onboard equipment of the station. Another important requirement—small size and weight of the instruments—was dictated by the known difficulties of delivering equipment to the surface of the moon.

CONDITIONS OF IMAGE TRANSMISSION

The moon as an object of TV transmission has a whole series of distinctive features. This was taken into consideration in the development of the camera. The characteristic trait of the lunar landscape is its immobility. Only shadows of the surface irregularities change their length as a function of the height of the sun, but this occurs relatively slowly: the length of the day on the moon is approximately 14 earth days and therefore the height of the sun changes only 0.5° per hour. In practice it is possible to speak of the transmission of a stationary image.

Lighting conditions on the moon have been adequately determined. The incident flux of solar light reaches its surface without being absorbed and creates an illumination of somewhat less than 150,000 lux on an area perpendicular to the incident flux.

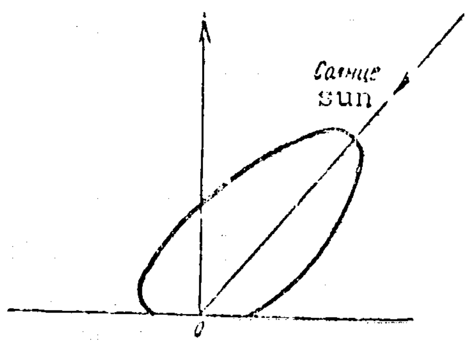

Figure 2

At the same time the reflected light beam strongly varies as a function of the height of the sun and the direction of observation. According to astronomical data [ref. #1], the characteristics of reflection (scattering curve) of the lunar surface have an unusual pear shape elongated towards the light source (fig. 2). These curves [or: indexes] are characteristic for strongly turned [dug up] rock and were obtained by earth observations of areas of the lunar surface having considerable dimensions. Although the extension of these data to the previously uninvestigated microrelief were questionable, they were necessary to take into consideration.

There is also another photometric feature of the lunar surface. Due to the low coefficient of reflection of the lunar rock, on the average equal to 0.1, as well as several other reasons, the range of brightness of details of the lunar relief in the majority of cases does not exceed 3.5. Thus, the problem was reduced to transmitting the images of low-contrast objects on a background whose average brightness varies to a considerable degree. In addition, it was necessary to consider the operation of the instrument under the transient conditions of early lunar morning at small [low] altitudes of the sun, when the character of the illumination can be very uncertain. Also, there was also the possibility of the station falling into a depression in the lunar surface where very low illumination could be expected.

All this required the development of a TV camera having a sufficiently high maximum sensitivity and a special system of automatically controlling this sensitivity (ASC) [=Automatic Sensitivity Control] which would serve as a means of adaptation to the variable and previously unknown conditions of operation.

PRINCIPLE OF OPERATION

The camera of *Luna-9* is an optico-mechanical scanning device which in its design can be attributed to instruments of mechanical television of phototelegraphy.

The selection of a mechanical system for image transmission from the surface of the moon was made after a thorough analysis and comparative tests of various image-transmission systems. Unlike electronic TV systems, the optico-mechanical system is slow acting, it is not capable of transmitting the image of fast-moving objects. However, in this case this condition best corresponds to the conditions of transmission of the still lunar landscape.

With the slow transmission of the image, the frequency band of the video signal is quite narrow and the signal can be transmitted by way of an economical radio-communication channel using an onboard low-power transmitter and directional antenna.

According to the operating conditions, it was necessary to have a circular, or in any case, sufficiently wide-angle field of view of the surrounding surface. In solving this problem with electronic TV cameras, the latter are equipped with additional subassemblies that make it possible to direct the position of its viewing axis by rotating either the whole camera or some optical element, e.g., a mirror installed in front of the lens. These subassemblies are, in fact, mechanical-scanning elements, often, of course, of not-too-high precision. In completely mechanical systems there is usually no need to base the functions of the coverage on any supplementary subassemblies—they are easily filled by a scanning device that leads to a substantial simplification of the equipment and a reduction in its weight.

It is known that mechanical systems where the effect of accumulation [storage] is not used have potentially considerably lower sensitivity than the electronic systems. At the same time, in the operation of a video signal having a bandwidth of several hundred Hertz, the absolute values of the sensitivity of the mechanical systems are on a level of good wide-band electronic devices where camera tubes of the vidicon type are used.

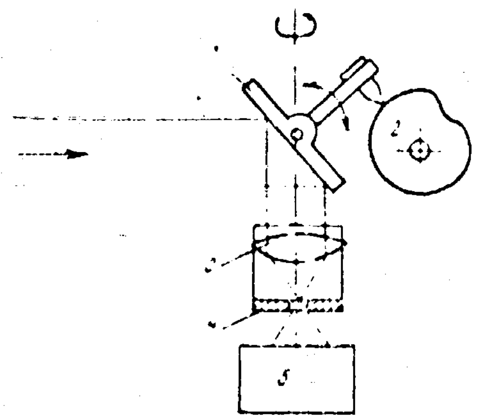

Figure 3

As a whole, the optico-mechanical system to a greater degree than the electronic can satisfy the strict requirements for weight, size, power, and operational reliability which are imposed on instruments of the automatic lunar station.

The image transmission in this camera is produced by means of a device consisting of a mirror *1*, cam *2*, and objective [lens] *3*, in whose image plane a stopping [cut-off] diaphragm *4* (fig. 3) is installed. Directly behind the diaphragm is a light collector *5*. The mirror accomplishes two movements: a fast one—oscillation along the vertical (line scanning) and a slow rotation in the horizontal plane—the frame panoramic scan, scanning the area as shown in fig. 4.

The major convenience of this type of scanning device is that the parameters of scanning are not a function of the characteristics of the lens. Specifically, the angle of coverage is not connected to the angle of view of the lens and can reach 360° at least in one direction. It also does not restrict the selection of the relative aperture and focal length of the lens which is made independent on the basis of the need of obtaining the assigned sensitivity, depths of focus, or size.

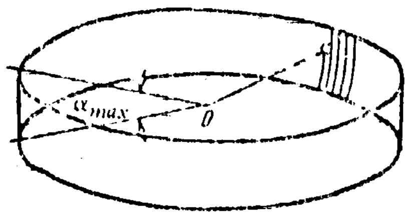

Figure 4

PARAMETERS OF THE SCANNING DEVICE

The cut-off diaphragm is placed at the center of the focal plane of the lens where the best image quality is assured. It forms a scanning element and determines the angular scan rate of the device. If F is the focal length of the lens and d the diameter of the diaphragm, then the angular resolving power can be found from the expression:

$$\Delta\alpha = \frac{d}{F} \text{ (radians)} \tag{1}$$

The sensitivity of the camera is a function in final analysis of the value of the luminous flux I_{min} incident on the light collector from objects having a minimum brightness B_{min}. The luminous flux is

$$I_{min} = \frac{d^2 \pi \tau B_{min} D^2}{4F^2} \tag{2}$$

Here D is the diameter of the [inlet aperture of] the lens; τ is its coefficient of transmission.

At the assigned value of $\Delta\alpha$, expression (2) is converted into:

$$I_{min} = \tau \Delta\alpha^2 B_{min} \frac{\pi D^2}{4} \tag{3}$$

As is seen in this case the basic design parameter which defines the minimum luminous flux is the area of the input aperture of the lens. Limitations on the size of the input [inlet] aperture and, consequently, on the sensitivity of this camera superimpose the need of assuring a definite depth of sharply transmittable space [depth of focus].

In normal orientation of the station, the closest areas of the lunar surface should be located at a distance of 1.5 m from the camera. Therefore, thelens of the camera having a focal length of F = 12.4 mm and a relative aperture of 1:3 is adjusted so as to provide a depth of focus from a distance of 1.5 m to infinity. As is seen from the obtained images, even closer objects—structural elements of the automatic lunar station itself—are quite sharply transmitted.

The diameter of the cut-off diaphragm which determines the angular resolving power of the instrument is calculated so as to obtain $\Delta\alpha$ = 0.06°, here at a distance of 1.5 m the camera permits details of the microrelief having a size of 1.5-2 mm to be resolved.

The selection of the vertical angle of view of the camera is a compromise between the tendency to the needed angular resolving power and to the assurance of the coverage of a sufficiently large part of the surface. Taking into consideration these factors and additional reasons made it possible to establish a value of vertical angle of coverage α = 29°. This angle is asymmetric with respect to the plane of the perpendicular axis of rotation of the camera (18° down, 11° up, see in fig. 5), so that the predominant image transmission of just the surface of the moon is provided.

A distinctive feature of the station is its inclination at a certain angle provided by the construction. The base of the station and its petal mechanism are made so that when the petals are open, the axis of the station and along with it also the axis of the TV camera are inclined approximately 16° to the local vertical when on a quite smooth horizontal field. This assures [provides] one of the closest areas of the lunar surface falling into the field of view of the camera and creates favorable conditions for the image transmission of the microrelief from a minimum distance from the camera (see fig. 5). This area with best resolution on the surface is well seen in all the obtained panorams.

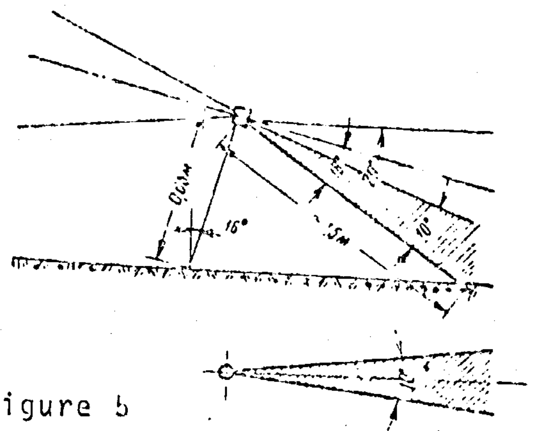

Figure 5

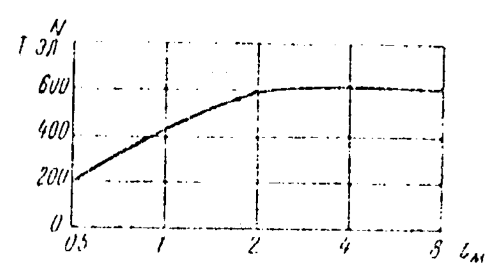

Figure 6

According to the images, it is evident that the selected vertical angle of coverage is close to the optimum. It yields the necessary representation of the general structure of the landscape and assures the obtaining of high-quality, we decipherable images of the details of the microrelief.

In the horizontal plane, the cam can produce a complete circular field of view [coverage] ($\beta = 360°$), therefore it is more correct to speak of obtaining circuloramic images. However, complete rotation of the camera was not made in all communication sessions, since part of the angle of view includes the "sky." In the selected process of coverage of the area, the image obtained at the receiving station has in the general case the relationship of the sides [ratio of the sides]:

$$n = \frac{\beta}{\alpha} \qquad (4)$$

For the camera under study which has a coverage of an area of 29° x 360°, $n = 12.5$. In other words, the transmitted panoramic image consisted of 12.5 square frames.

The definition of the image at this angle of coverage and the angular resolution were no less than 500 lines per trace and 6000 lines in the entire panorama. The definition could be estimated according to a standard test table whose dimensions were inscribed in an angle of 29°. The curve charactering the definition as a function of the distance to the object or, which is the same thing, the depth of focus of the instrument is shown in fig. 6.

DRIVE OF THE MECHANISM

The scanning device of the camera was driven by one motor *M* by means of a multistage reduction gear *R* (fig. 7). The requirement of high economy and consequently high efficiency of the drive stipulated the use of a DC commutator motor, a miniature machine of the type DPT-2 [ДПТ-2] having all the necessary characteristics was therefore used. The high stability of the speed of this motor was provided by means of a synchronization unit *SU* made according to the simplified circuit [scheme] of phase self-adjustment.

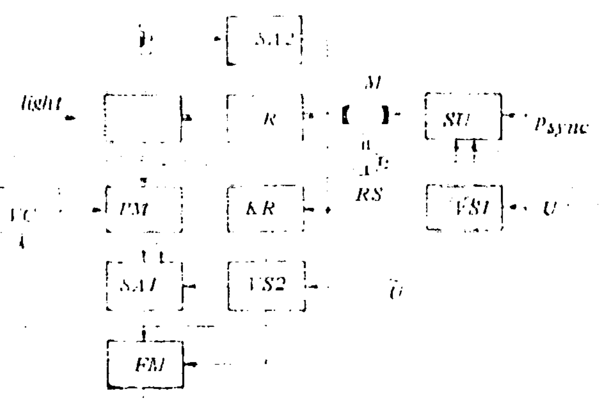

Рис. 7

Figure 7

The circuit supplies the motor *M* with width-modulated DC pulses that are formed as a result of comparing the pulses coming from the rotation sensor *RS* installed on the motor shaft with the reference pulses of highly stable 200-Hz frequency coming from the onboard timer. The synchronization unit is powered from the self-contained onboard voltage stabilizer *VS1*.

In the synchronized mode the motor spins at a speed of 3000 rpm, then the scanning speed is 1 line per second. The instability of the speed motor shaft caused by the inaccuracy in the operation of the synchronization unit does not exceed 1/20 revolution.

The cam mechanism serves as a basic, and, it should be noted, a variable load for the motor. The variable load makes the operation of the synchronization unit more difficult and can become a source of undesirable fluctuations in the mechanical system. Therefore, measures were taken to reduce the irregularity of the momentum primarily due to the reduction of the difference in radii of the cam. At a mean diameter of the cam equal to 27 mm, a difference in radii of up to 3 mm could be introduced.

Since the reverse path is approximately 10% of the rotation of the cam, the angle of lift of its profile in reverse is considerably less than the angle of jamming. This condition makes it possible then in its turn to transmit the image without difficulties and in reverse rotation of the cam by reversing the motor. Also, the possibility of asynchronous rotation of the motor was provided in the camera when the motor is connected directly to the onboard power source. In this case its speed was increased approximately by a factor of 4. The selection of the necessary speed and direction of scan was produced on commands from earth. The camera provided operation in the following modes:

1. Image transmission with a speed of 1 line/sec in coverage in one direction. The time necessary for complete circular coverage is 100 min.

2. Image transmission with the same speed and coverage in the reverse direction.

3. Accelerated mode of transmission—fast forward or reverse. Time of

complete rotation [revolution] 20-25 min.

The presence of the different modes makes it possible to control the instrument by scanning the most interesting places of the image at a minimum loss of time which is especially valuable in the limited power possibilities of the station. The third mode is the service mode and is not designed for obtaining an image, but for operative selection of the required sector of the panorama following observation of the video signal. The switching on of this mode of operation is possible at those times when transmission of telemetry information is being conducted. In doing this, time is not generally lost in the selection of interesting places of the panorama.

SIGNAL SHAPING

The light collector in the camera is a photo-electronic multiplier of the head-on type (ΦЭУ-54 [FEU-54 = PM-54]) especially developed for this camera. It has a rigid louver construction of dynodes and small size: length 90 mm and diameter 22 mm. This PM is distinguished by high time and temperature stability and also the small time necessary for the parameters to become steady after turning on.

The majority of FEU-54 units have an integral sensitivity of not less than 50 a/lu at a power voltage of 1700 v, the maximum of the spectral sensitivity lies in the region of 550 mμ.

In this camera small luminous fluxes are registered that reach, in an extreme case, a value on the order of 10^{-10} lu. Accordingly, the signal current generated by the PM is also measured in thousandths of microamps. At such a small signal current, the PM dark current can be comparable to it in order of magnitude and appreciable affect the signal-to-noise ratio and the temperature stability of the parameters, therefore, special measures were taken that make it possible to reduce the PM dark current. They proved to be quite effective and enabled operation on DC without signal modulation.

The characteristics of the light-to-signal conversion is made in the camera logarithmically and consequently provides linear transmission not of the brightnesses of the objects, but rather of their optical densities. It is known that this type of half-tone transmission is distinguished by the improved quality of image reproduction. Taking the logarithm of the video signal takes places due to the nonlinearity of two circuits: PM and video signal preamplifier (SA1).

For this purpose, the PM is specifically placed in a nonlinear mode of operation by matching the power supply with its individual dynodes, however, the degree of nonlinearity here is inadequate. Therefore, subsequent formation [shaping] of the logarithmic characteristic of transmission is produced in a single-stage amplifier of the video signal which is a direct-heating electron tube—a super-economical low-voltage pentode having substantially nonlinear anode-grid characteristic. The combination PM-electron tube is very favorable for matching their output and input resistors [resistances] and providing stable amplification of DC in a wide temperature range.

The narrow band of the video signal frequency stretching nominally from 0 to 250 Hz and the high input resistance of the amplifier made it possible to establish a relatively high ohmic (tens of megohms) load for the PM where even at small signal currents, voltage is developed up to several volts. The span [coverage] of the anode-grid characteristic [or: performance curve] of the tube here is practically completely used and no large coefficient of amplification is required from it. At the input of the tube, the voltage of the video signal is created that is adequate for controlling the subsequent stage--the frequency modulator (FM).

In this stage, modulation of the low-frequency subcarrier is produced equal to 1.5 kHz. For the [illegible] tuning of the communication channel, a change in the value of deviation of the subcarrier from 200 to 800 Hz was provided. The frequency-modulated signal from the camera output goes to the radiotransmitter where the phase modulation of radio-frequency of 185 MHz is produced.

The amplifier stage also fulfills other functions. In it is produced a mixing of the phasing pulse of reverse into the video signal; this pulse is obtained by means of a contact pickup located on one shaft with a cam forming a kipp relay (KR). The units examined are powered by voltage stabilizer VS2.

AUTOMATIC SENSITIVITY CONTROL (ASC)

The uncertain lighing conditions of the operation of the instrument caused a system of automatic control of camera sensitivity to be developed. Actually, a very broad range of brightnesses of the transmitted objects covering more than 3 orders of magnitude that can be encountered on the surface of the moon made the realization of the command control of sensitivity of the instrument very difficult, however, this is not the main point.

The command control unavoidably provides operation following a method of trial and error, and consequently loss of a certain part of information which is especially inconvenient in the restricted times of transmission and volume of information to be transmitted.

It was necessary to also take into consideration that the camera continuously transmit the panoramic image where the direction of sighting of the scanning device ranges from an angle of 0 to 360°. Here, in accordance with the scattering curves, the mean brightness of the surface areas transmitted by the camera also varies. Thus, there arises the necessity of controlling the sensitivity in the transmission process of one panorama and it becomes clear that the command, ordinarily a discrete change of sensitivity could appreciably deteriorate the quality of the obtained panoramic image.

In the device under study, automatic control was conducted by means of a change in the PM sensitivity as a function of the average brightness of the subjects to be transmitted.

For the ASC system, a circuit of a classic exposure meter was selected whose sensor is a photoresistor equipped with a diaphragm limiting its field of view. The photoresistor is in the upper portion of the optico-mechanical scanning device and revolves [rotates] along with it.

From practical photography it is known that the formal determination of the exposure by means of an exposure meter can sometimes lead to substantial errors; these are called exponometric errors. They arise due to the non-correspondence of the average illumination of the entire frame of image and of that part of it which is the primary purpose of the photograph. Space TV is especially subjected to exponometric errors in some of its applications. In obtaining images of heavenly bodies, part of the fram may have a well lit surface, and part—utterly dark space. The section of space proves to have a strong effect in the average illumination of the frame [scene], which with an automatic exposure meter causes an "overexposure" of the useful portion of the image.

In the panoramic camera, special attention was directed to the development of the ASC system so as to exclude if possible or reduce exponometric errors. First of all, after a series of experiments, an optimum angle of view was selected for the photosensor (see fig. 5). It does not cover the entire angle of view of the camera, but only 10° x 10° and coincides approximately with the lower third of the frame. This location makes it possible for it to be protected from the effect of the dark "sky" as well as from incident solar rays and highlights (at low altitudes of the sun).

Considering that the calibration of the ASC takes place under terrestrial conditions which naturally differ from the lunar conditions, a command control of the mode of operation of the ASC system was introduced to exclude any possible errors and increase reliability. One of the commands increases the sensitivity of the instrument with respect to nominal, another reduces it. The change in transmission characteristics here are illustrated by fig. 8 (Curves *I*, *II*, *III*).

Figure 8

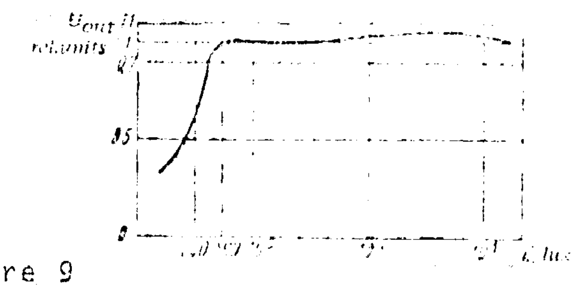

Figure 9

One should note that the logarithmic transmission characteristic [performance curve] of the instrument makes it little sensitive to inaccuracy of the ASC system and in the schematic relationship simplifies its plotting.

The most effective method of controlling the sensitivity of the PM is the change in the total voltage supplying its dynodes. Here there is a gradual [step-by-step] dependence of the coefficient of PM amplification on the power supply. If the performance curve of the light-to-signal conversion is indeed logarithmic, then there is a linear dependence between the conntrolling effect (voltage at the PM) and the output signal. In this case, there also occurs: photoresistor PR creates a signal approximately proportional to the average brightness which is powered through the DC power amplifier SA2 by the high-voltage converter VC from which the voltage is fed to the PM.

The camera provides normal image transmission in the illumination range from 80 to 150,000 lux for a surface having the characteristics of the lunar soil. Figure 9 shows the curve describing the operation of the AES system. It shows the amplitude of the output video signal U_{out} drawn as a function of the illumination of the object of transmission E.

When E < 500 lux, the ASC system does not operate, but normal image transmission is possible by giving a command to increase the sensitivity. The minimum illumination at which transmission of a satisfactory image is assured is approximately 80 lux.

The ASC system unavoidably excludes any information as to the mean brightness of the objects to be transmitted from the output signal; however, this information may be of interest. Therefore, indirect transmission of this information was provided in this camera; the carrier of this information is the width-modulated phasing pulse of reverse. For this purpose the signal from the photoresistor, having passed through amplifier SA2, simultaneously reaches the circuit controlling the pulse width of the kipp relay KR.

CONSTRUCTION OF THE CAMERA

The TV camera has a cylindrical shape (fig. 10). The lower portion of the camera is a container of magnesium alloy with a flange and hermetic joint. The camera is partially (up to the level of the flange) fused into the body of the station, the flange providing hermetic sealing. The upper exterior portion of the camera projecting beyond the branches of the hermetic body of the station is gilded, which reduces its heating due to heat radiated by the lunar surface and the sun. In addition, for protection from the incidence of direct solar rays at great altitudes of the sun, a heat-insulating screen was installed on the upper portion of the TV camera. The calculated temperature range at which the camera must operate lies within temperatures of $t°$ =-120 to +50°C. Practical tests showed that normal image transmission can occur even at +80°C.

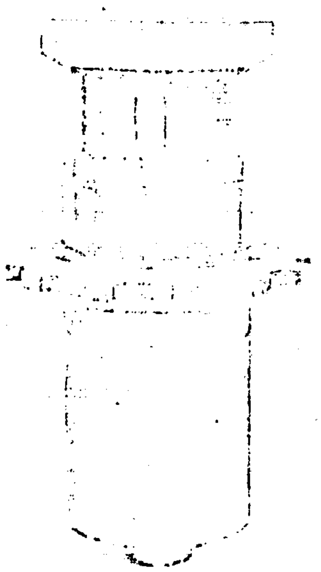

Figure 10

The internal portion of the camera contains all necessary units and subassemblies shown in the block diagram. Voltages of the power source, synchronized frequency, and controlling commands are fed through the thermojoint into the camera.

From here the output frequency-modulated signal arrives at the radio unit of the station.

Thus, the internal portion of the camera is not connected with the hermetic volume of the station's body. This construction solution required taking the necessary measures to guarantee its normal operation under the conditions of the vacuum of space.

It is known that at very high vacuum (below $p = 10^{-8}$ mm Hg) there arise a number of phenomena which in the final analysis lead to a sharp rise in the friction of operating mechanisms right up to their jamming and welding of individual parts. For an instrument having an optico-mechanical scanning device driven by a DC commutator motor, the effect of high vacuum was especially dangerous. At the present time special lubricating and construction materials are being developed that make it possible to create mechanisms that operate reliably in a high vacuum. However, in this case they are almost not used and the problem of protection here was solved in another way. In spite of the fact that the internal volume of the camera is non-hermetic in practice, its construction is such that the pressure on the inside cannot fall below 10^{-3}—10^{-5} mm Hg, i.e., reaching those values at which the damaging effects originate. This method of protection (it may be called vacuum screening) was first tested under terrestrial conditions and in experimeental flights of cameras aboard satellites, where its reliability was shown.

The external screening cowl of the camera has a complex construction. Its base is a rigid metal cylinder with windows that provide the necessary angle of coverage for the scanning device (fig. 11). The windows are stretched [over] by a thin (50μ) transparent *lavsan* [Russian acronym for: Laboratory of High Molecular Compounds of the Academy of Sciences of the USSR; a term for a type of plastic] film which does not introduce any optical distortions in the image to be transmitted and not only provides vacuum screening, but also protection from dust and mechanical damage.

Figure 11

All mechanical elements of this scanning device are made with high accuracy, but are not of [high] precision. In this camera, the error of the scanning device does not exceed 1/3 of the TV element.

In the development of the electronic portion, special attention was given to attaining maximum simplicity and reliability of circuit solutions. The rational construction of the mechanical and electronic portions of the instrument made it possible to satisfy the initial technological requirements with a considerable surplus.

The weight of the camera is 1300 grams and its size without flange—

80 x 205 mm. The power required does not exceed 2.5 W.

RESULTS OF OPERATION

The operation of the panoramic cameras aboard the automatic lunar stations *Luna-9* and *Luna-13* completely confirm the validity of the calculations and suppositions assumed [made] in their manufacture. Specifically, one should note the optimization of this TV system, its correspondence to conditions of operation aboard the station and the scientific problems posed. Although the total volume of transmitted information was comparatively small (several panoramas or more than 40 square frames), it made it possible to obtain qualitatively new and valuable information concerning the characteristics of the lunar suface. The TV system of the American spacecraft *Surveyor* that became the second station after *Luna-9* to achieve a soft landing on the moon transmitted more than 10,000 frames, but did not substantially add any new information to the already obtained results.

With the station *Luna-9* stereoscopic images were transmitted for the first time of quite small formations of the lunar surface. Part of these images was obtained in accordance with the intended program of operation. For this purpose a dihedral [two-faceted] mirror providing a stereobase for very narrow (approximately 4°) of the sectors of the panorama was installed in the field of view of the camera. However, the most abundant stereoscopic information was obtained due to a shift [in the position] of the station through the period of time that passed between the transmission of the first and third panoramas. This shift, the cause of which is not completely led to the appearance of a stereobase having a value of 9 cm. Of course, the first and third panoramas are not quite accurate stereopairs, since the height of the sun and consequently the length of the shadows when they were transmitted were different. Nevertheless, in examining this stereopair, the eye adapts itself to its peculiarity giving preference to the shadows of one of the images, at the same time the volumicity [3d effect] of the observed objects appears to a full degree. The stereo effect also facilitates considerably the deciphering and photogrammetric development of the image, the results of which are presented elsewhere [ref. #2].

The panoramic camera of *Luna-9* was the first high-quality device of mechanical television that operated practically in space. Various "terrestrial" applications can also be found for such cameras, which opens new interesting opportunities in applied television.

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